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Subject Expert: Norman Rohrig Approval: Signature on File Date: 03/16/2004 Judson L. Kenoyer, Task 3 Manager Concurrence: Signature on File Date: 03/17/2004 Richard E. Toohey, Project Director Approval: Signature on File Date: 03/17/2004 James W. Neton, OCAS Health Science Administrator	Supersedes: None

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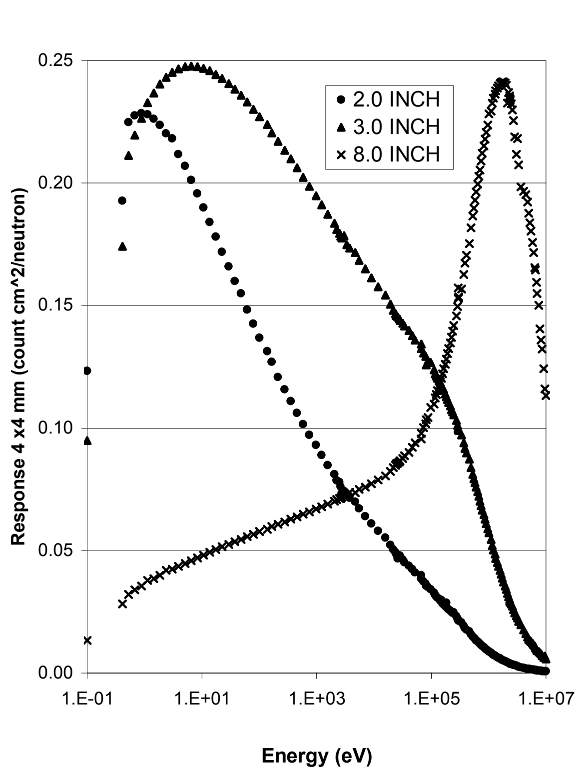
Reanalysis of Hankins MTR Bonner Ball Surveys

Norman Rohrig, November 2003

Dale Hankins made a series of neutron field measurements (Hankins 1961) with 2-, 3-, and 8-in. diameter Bonner balls around the Idaho National Engineering and Environmental Laboratory (INEEL) Materials Test Reactor (MTR). The balls were covered with a cadmium shield which eliminates thermal neutrons below 0.41 eV. These 25 measurements were mostly around the MTR floor, but one was at Experimental Breeder Reactor (EBR-I) through 9 feet of concrete and three were at the Engineering Test Reactor (ETR). Six other measurements labeled A to F also include a thermal neutron component determined from the difference of a bare and a cadmium covered detector.

Since then, significant improvements have been made to understanding the responses of these detectors to neutrons of all energies and, in particular, intermediate neutrons. The Hankins data have been reanalyzed using detector responses calculated by Hertel and Davidson (1985) for 171 energy groups from thermal to 17.3 MeV, as shown in Figure 1. This figure shows a higher sensitivity for the 2" and 3" detectors at low energies as compared to Figure 2 in Hankins' (1961) paper. These calculated response curves are more complete than the ones available in 1961, particularly below 100 keV neutron energy where monoenergetic neutron spectra are not available.

Figure 1: Energy response of Bonner spheres



These calculated response matrices are for 4 x 4 mm lithium Iodide detectors, whereas the Hankins data used 2 x 8 mm detectors. Hertel and Davidson (1985) also calculated responses for ½- x ½-in. detectors, which have larger response by about a factor of the detector surface area. Because most reactions in the detector are on the detector surface, the calculated neutron fluences and resulting dose equivalents are reduced by roughly a factor of 2 for all detectors and energies to account for the different size detectors used by Hankins (1961).

Limited determination of the energy spectrum can be made with only three measurements of neutron response and the additional requirement that the number of neutrons in any energy region cannot be negative. Following Hankins (1961), the fraction of the summed response in each of the three balls (2-, 3-, and 8-in) is calculated for a fission spectrum, and a 1/E slowing down spectrum, which are expected in the reactor. The 1/E spectrum was assumed to go to 0.6 MeV and was divided into two sections at 10 keV. To fit the Hankins data, the fission spectrum of the form

$$\varphi(E) = \frac{1}{E^{1/2}} e^{-E/T}$$

was used above 0.6 MeV. For a typical fission spectrum, the characteristic temperature T is about 1.3 MeV, which was used in these calculations. The measured detector responses were expressed as a linear combination of the three spectra (1/E 0.4 eV - 10 keV, 1/E 10 - 600 keV, and fission) and solved.

To determine the dose equivalent, one must multiply the fluence at each energy by the dose equivalent conversion factor (DECF) for that energy and add them up (i.,e. do an integral). The official tabulations provide conversion factors at limited energy values. Ing and Makra (1978) provide a parameterization for dose equivalent with energy which we use here. Figure 2 compares this parameterization to Monte Carlo calculations reported in NCRP38 and by Auxier et al. (1968).

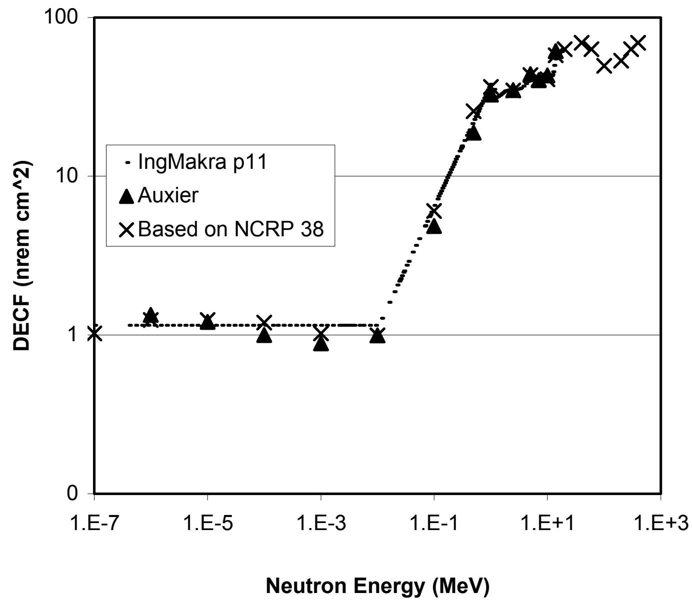
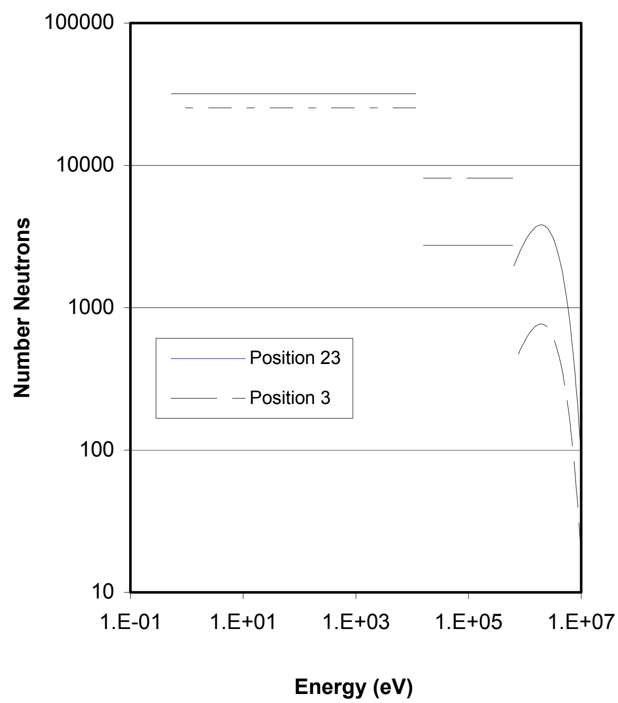


Figure 2: Neutron Dose Equivalent Conversion Factor (nrem cm^2)

Table 1 lists measured values from Hankins (1961) and the resulting reanalyzed dose equivalents from the three energy groups and their sum. Table 2 provides the same information for the six locations where Hankins provided thermal measurements. The thermal values are as reported by Hankins. Figure 3 shows the resulting neutron spectra for locations 3 and 23, which have higher doses and nearly the maximum low energy and fission components, respectively.

Figure 3: Sample MTR Spectra from Reanalyzing Hankins Bonner Measurements



Another survey at the MTR measured the fast neutron field (Sommers 1959a) using a Rudolf counter described as “a dose rate instrument, sensitive to neutrons in the range of 0.2 to above 10 MeV” (Sommers 1959b). This has been remembered as a detector about the size of a soda can with the end painted red. The Dennis and Loosemore (1961) detector shown in Figure 4 is believed to be what was known as the Rudolf counter at the INEEL. It detects hydrogen recoils and has a threshold energy of about 0.2 MeV. Using 0.2 MeV as the division line between fast and intermediate neutrons to correspond to that for this instrument, Figure 5 shows the correlation of the recalculated 0.4 eV – 10 keV and 10-200 keV neutron dose equivalent rates with the recalculated fast neutron dose equivalent rates along with the correlation of the Hankins analysis intermediate to fast neutron dose equivalents. Also shown are the Hankins thermal dose equivalent rates compared to the recalculated fast neutron dose equivalent rate.

Table 1. Data from Hankins (1961) and reanalyzed doses.

Location*	Total CPM	% Total CPM			Dose equivalent (mrem/hr)			
		2"	3"	8"	0.4 eV-10 keV	0.01-0.6 MeV	Fission	>0.4 eV
EBRI 1	2935.6	31.3	49.9	18.8	0.208	0.337	0.300	0.845
2	491.7	30.7	49.5	19.8	0.034	0.064	0.066	0.163
3	2854.1	31	49.4	19.6	0.200	0.304	0.462	0.966
4	2966.2	30.6	49.1	20.3	0.204	0.340	0.556	1.100
5	2315.2	29.8	49.1	21.1	0.152	0.375	0.350	0.876
6	1698.5	29.9	48.9	21.2	0.113	0.247	0.314	0.674
7	611.1	29.6	48.4	22	0.040	0.084	0.149	0.273
8	981.9	29.5	48.3	22.2	0.064	0.136	0.250	0.450
9	5539	28.9	48.2	22.9	0.350	0.933	1.338	2.621
10	662.9	29.1	48.1	22.8	0.042	0.100	0.176	0.319
11	5700.6	29.5	48	22.5	0.376	0.699	1.699	2.773
12	7603.3	28.7	47.9	23.3	0.477	1.257	2.056	3.789
13	6185.1	29.3	47.8	23	0.404	0.763	2.005	3.172
14	2694.6	29.6	47.6	22.8	0.180	0.258	0.973	1.411
15	3116.3	28.9	47.5	23.6	0.200	0.412	1.071	1.683
16	8877.1	28.5	47.4	24.1	0.556	1.337	3.021	4.913
17	2083.4	29	47.3	23.7	0.135	0.241	0.787	1.163
18	2581.4	28.4	47.3	24.3	0.161	0.391	0.904	1.456
19	1627.8	28.1	47.3	24.6	0.099	0.275	0.548	0.923
20	4848.1	28.2	46.8	25	0.302	0.665	2.008	2.975
ETR 21	111.3	27.7	46.5	25.8	0.007	0.017	0.048	0.072
22	1494.8	28.2	46.2	25.6	0.094	0.158	0.750	1.003
23	4427.9	26.5	45.6	28	0.252	0.774	2.295	3.321
ETR 24	199.2	26	44.7	29.3	0.011	0.032	0.124	0.166
ETR 25	210.9	25	44	31.1	0.011	0.038	0.144	0.193
				Total	4.672	10.236	22.393	37.300

* At MTR, unless otherwise noted.

Table 2: Data from Hankins (1961) with thermal neutron measurement and reanalyzed doses.

Location	CPM			Dose Equivalent (mrem/hr)				
	2"	3"	8"	Thermal	0.4eV-10 keV	0.01-0.6 MeV	Fission	Neutron
A	877	1473	700	0.11	0.19	0.56	0.67	1.42
B	196	317	153	0.02	0.04	0.07	0.24	0.35
C	778	1293	647	0.09	0.17	0.41	0.87	1.46
D	3518	5973	3108	0.32	0.76	2.33	3.94	7.03
E	3482	5734	3064	0.21	0.77	1.50	5.36	7.64
F	557	925	470	0.06	0.12	0.29	0.67	1.08

The R^2 values shown on the trendlines are the fractions of the variance which is explained by the lines. For the reanalyzed data the R^2 values are 92% and 86% compared to only 50% for the original Hankins analysis, demonstrating that the reanalysis is a better fit. The slope of the trendlines is a dose weighted average of the ratios for the various datapoints. Table 3 provides comparisons of the different components of the neutron dose equivalent rate.

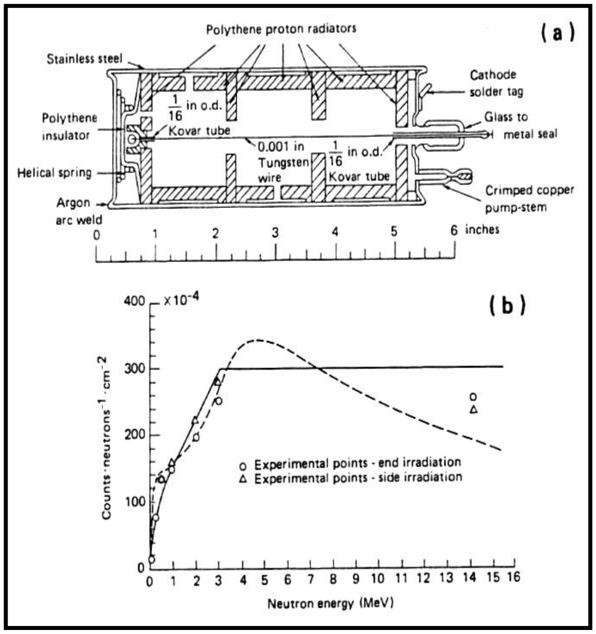


Figure 4: Dennis/Loosemore detector known as the Rudolf at the INEEL with its energy response curve.

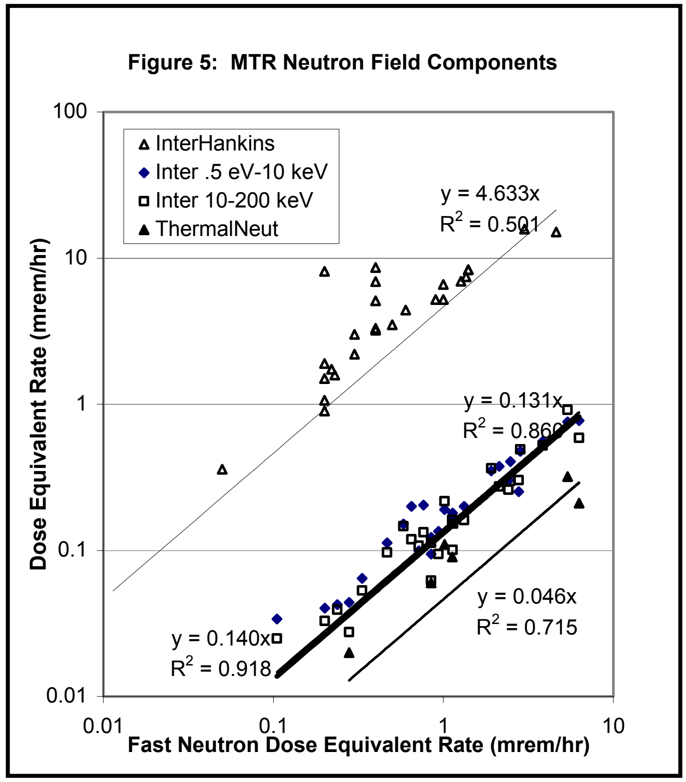


Table 3: Ratio of Neutron Dose Equivalent Rates at the MTR

	Thermal Fast	0.4 eV-10 keV Fast	10-200 keV Fast	Total Fast
Trendline	0.046	0.140	0.131	
Average	0.071	0.175	0.147	1.393
Minimum	0.033	0.066	0.073	1.226
Maximum	0.108	0.408	0.259	1.738
St Dev	0.025	0.074	0.050	0.121

The Interactive RadioEpidemiology Program (IREP), which calculates the probability of causation, uses certain neutron energy groups. The dose equivalent rate and the fraction of the dose equivalent in each of these regions are listed in Table 4. For the numbered locations where no thermal neutron value is available, the average value for the ratio of thermal to fast of 0.71 from Table 3 is assumed.

The NTA neutron dosimeters in use when the MTR was operating at the INEEL respond only to neutrons above 0.5 to 0.8 MeV. For the MTR spectra, Table 4 lists the fraction of neutron dose equivalent above 0.8 MeV, which would be picked up by the NTA film, that varies from 35% to 66% depending on the location with a mean of 0.52 and a standard deviation of 0.08. The remainder of these low-energy neutron fields would probably not be detected by the NTA film because of its 0.8-MeV threshold.

Sommers (1962) reported thermal and fast neutron dose equivalent rates and gamma dose rates around the MTR beam lines. The thermal measurements near beams are believed to not be representative of the workplace. Figure 6 shows the correlation of fast neutron dose equivalent to the gamma dose for these measurements. The fast neutron component was insignificant for several of the measurements. These points are shown by the triangles at 0.5 mrem/hr, ½ of the smallest measured value. Including all the data in a Shapiro and Wilk W test for normality (Gilbert 1987) gives a slightly better result for a normal distribution rather than a lognormal distribution. The fast neutron dose is 0.419 ± 0.347 times the gamma dose. Combining these results, with those of Table 3, one can conclude that the ratio of total neutron dose equivalent to gamma dose is 0.58 ± 0.48 at the 1 sigma level. The variation on the relative neutron components are buried by the fast neutron to gamma variation.

The IREP program uses equivalent dose as defined in ICRP 60 using the radiation weighting factor w_R defined in Table 1 of ICRP 60. The NIOSH External Dose Implementation Guide (NIOSH 2002) provides conversion factors from ambient dose equivalent H^*_{10} to the organ equivalent dose, and ICRP 74 (ICRP 1995) provides a calculation of the ambient dose equivalent so we can construct the ambient dose equivalent for these spectra. The ratios of the neutron ambient dose equivalent (ICRP 74) and the neutron dose equivalent (NCRP 38) are shown in Table 4. For the 10 to 100 keV energy group, the ratio of the ambient dose equivalent to the neutron dose equivalent is 1.08, while for the above 2 MeV energy group it is 1.121. For the groups where the spectra are not simple multiples of each other there is some variation with location.

Figure 5: Correlation of Fast Neutron Dose Equivalent to Gamma Dose at MTR

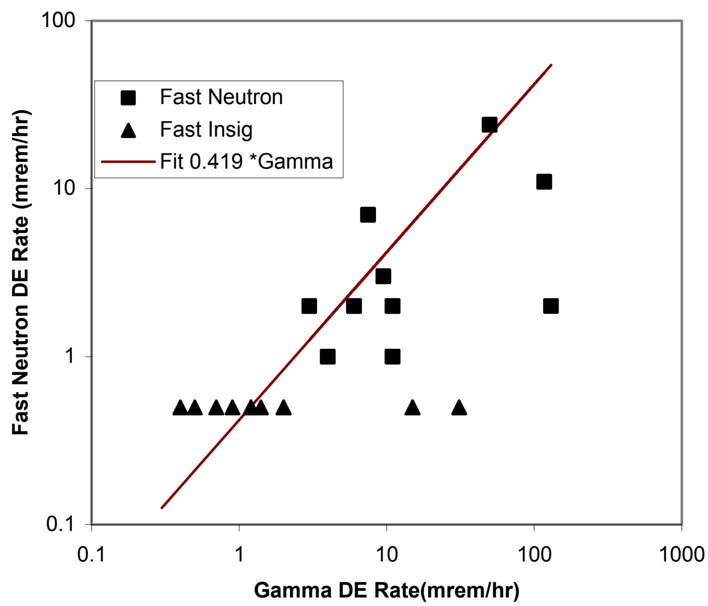


Figure 7: ICRP 74 Ambient Dose Equivalent Conversion Factor

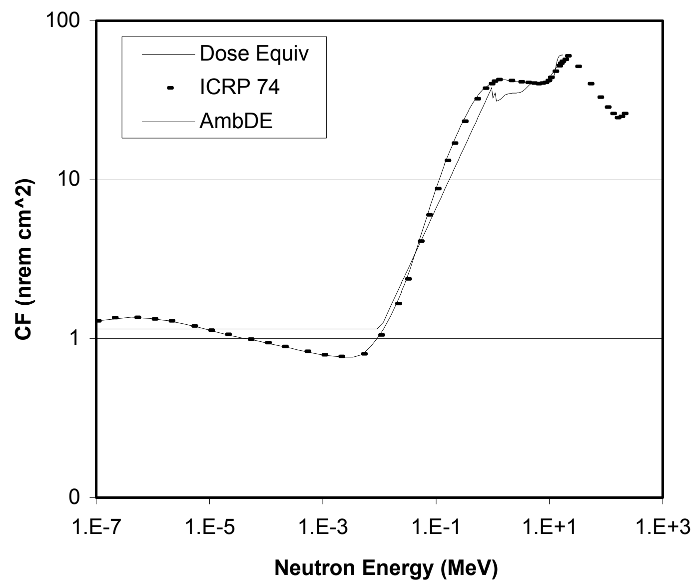


Table 4: Distribution of MTR neutron dose equivalent among IREP energy groups, NTA response, and ratio of equivalent dose to dose equivalent.

Location*	Dose Equivalent Fraction >10keV	10 keV-100 keV	100 keV-2 MeV	2M-20M	IREP Energy Interval Ambient Dose Equiv / Dose Equiv <10keV	100 keV-2 MeV	Spectrum	Fractional NTA Sensitivity >0.8 MeV
EBRI 1	0.28	0.079	0.47	0.17	0.89	1.38	1.14	0.32
2	0.24	0.077	0.49	0.19	0.88	1.37	1.14	0.36
3	0.24	0.062	0.47	0.23	0.87	1.35	1.13	0.42
4	0.22	0.061	0.47	0.24	0.87	1.35	1.13	0.45
5	0.21	0.084	0.51	0.19	0.88	1.37	1.16	0.35
6	0.21	0.072	0.50	0.22	0.87	1.36	1.15	0.41
7	0.19	0.060	0.49	0.26	0.86	1.34	1.14	0.48
8	0.19	0.059	0.49	0.26	0.85	1.34	1.14	0.49
9	0.18	0.070	0.51	0.24	0.86	1.35	1.15	0.45
10	0.18	0.062	0.50	0.26	0.85	1.34	1.14	0.49
11	0.18	0.049	0.48	0.29	0.84	1.33	1.13	0.54
12	0.17	0.065	0.51	0.26	0.85	1.35	1.15	0.48
13	0.17	0.047	0.48	0.30	0.84	1.32	1.13	0.56
14	0.17	0.036	0.46	0.33	0.83	1.31	1.12	0.61
15	0.17	0.048	0.49	0.30	0.83	1.32	1.13	0.56
16	0.16	0.053	0.50	0.29	0.83	1.33	1.14	0.54
17	0.16	0.040	0.48	0.32	0.82	1.31	1.12	0.60
18	0.16	0.052	0.50	0.29	0.83	1.33	1.14	0.55
19	0.15	0.058	0.51	0.28	0.84	1.34	1.14	0.52
20	0.15	0.044	0.49	0.32	0.82	1.32	1.13	0.59
22	0.15	0.031	0.47	0.35	0.80	1.30	1.12	0.66
23	0.13	0.045	0.50	0.33	0.80	1.32	1.14	0.61
A	0.20	0.075	0.51	0.22	0.92	1.36	1.20	0.41
B	0.17	0.039	0.47	0.32	0.92	1.31	1.17	0.59
C	0.17	0.055	0.49	0.28	0.92	1.33	1.19	0.52
D	0.15	0.065	0.52	0.27	0.92	1.34	1.20	0.50
E	0.13	0.039	0.49	0.34	0.91	1.31	1.18	0.64
F	0.16	0.052	0.49	0.29	0.92	1.33	1.19	0.55
ETR 21	0.14	0.046	0.49	0.32	0.81	1.32	1.13	0.59
ETR 24	0.12	0.037	0.49	0.35	0.78	1.30	1.13	0.65
ETR 25	0.11	0.038	0.50	0.35	0.77	1.30	1.13	0.65
Average	0.18	0.056	0.49	0.28	0.86	1.33	1.15	0.52
Minimum	0.13	0.031	0.46	0.19	0.80	1.30	1.12	0.35
Maximum	0.24	0.084	0.52	0.35	0.92	1.37	1.20	0.66
St Dev	0.030	0.013	0.015	0.043	0.037	0.020	0.026	0.08

* At MTR unless otherwise noted.

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